GEORGIA INSTITUTE OF TECHNOLOGY
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SPONSORED PROJECT INITIATION

Date: 12/30/80

Project Title: Millimeter Wave Sensor Study

Project No: A-2830

Project Director: Mr. J. M. Schuchardt

Sponsor: Standard Elektrik Lorenz AG; Stuttgart, Germany

Agreement Period: From 11/20/80 Until 3/19/81

Type Agreement: Contract dated 11/20/80; SEL Order No. 613609-96-524701-788322956

Amount: $15,000

Reports Required: Draft Final Report

Sponsor Contact Person (s):

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Defense Priority Rating: None

Assigned to: EML/RSD (~~School~~/Laboratory)

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SPONSORED PROJECT TERMINATION

Date: 5/14/81

Project Title: Millimeter Wave Sensor Study

Project No: A-2830

Project Director: Mr. J. M. Schuchardt

Sponsor: Standard Elektrik Lorenz AG; Stuttgart, Germany

Effective Termination Date: 5/31/81

Clearance of Accounting Charges: 5/31/81

Grant/Contract Closeout Actions Remaining:

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Technical Description of Report

This report covers a brief investigation of the use of a nonradiating imaging sensor for reconnaissance purposes. Three millimeter wave frequencies were examined; 95 GHz appears best.

Final Technical Report
Project A-2830

MILLIMETER WAVE SENSOR STUDY

J. M. Schuchardt

April 1981

for

Standard Elektrik Lorenz AG
Stuttgart, West Germany

by

Georgia Institute of Technology
Engineering Experiment Station
Atlanta, Georgia 30332

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SUMMARY

This investigation has examined the feasibility of using a passive (radiometric) imaging system aboard a reconnaissance vehicle. The mechanical and electrical parameters for a sensor candidate are given herein. The parameters are derived from an examination of available space, hardware state-of-the-art and given altitude and velocity profiles. The preferred sensor antenna uses 3 continuously rotating 23 cm diameter apertures [1] to gather the image data.

For the cases examined, a 40 m^2 (x 0.7)* metal target and a water/land interface, calculations were made of sensor requirements, scene contrast, and receiver sensitivity. These data indicated that very good performance is possible for the water/land interface in clear and foggy weather. Metal target detectivity is good in clear and foggy weather conditions at an altitude of 600 m and good in clear weather at 1200 m. With an 80 m^2 (x 0.7) metal target, good detection can be achieved at 1200 m altitude, even in fog.

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*The 0.7 factor is used to account for geometric factors causing only 70% of the surface area to reflect sky temperatures.

1.0 INTRODUCTION

Battlefield surveillance in adverse weather is improved with the use of a passive (radiometric) millimeter wave sensor when battlefield status and decision-making data are often most needed. A millimeter wave capability ensures that such data can be obtained even in overcast and fog conditions when infrared sensors are limited. This investigation examined the preliminary design feasibility of a line-scan sensor that could operate in a remotely piloted/programmed drone vehicle. The atmospheric windows at 35, 95, 140, and 220 GHz were examined. Sensor performance was traded off for both the clear and fog (overcast) conditions.

The basic conditions examined are listed in Table 1. Here, the vehicle velocity and altitude parameters are listed; the desired mapping area is given, and target parameters are presented.

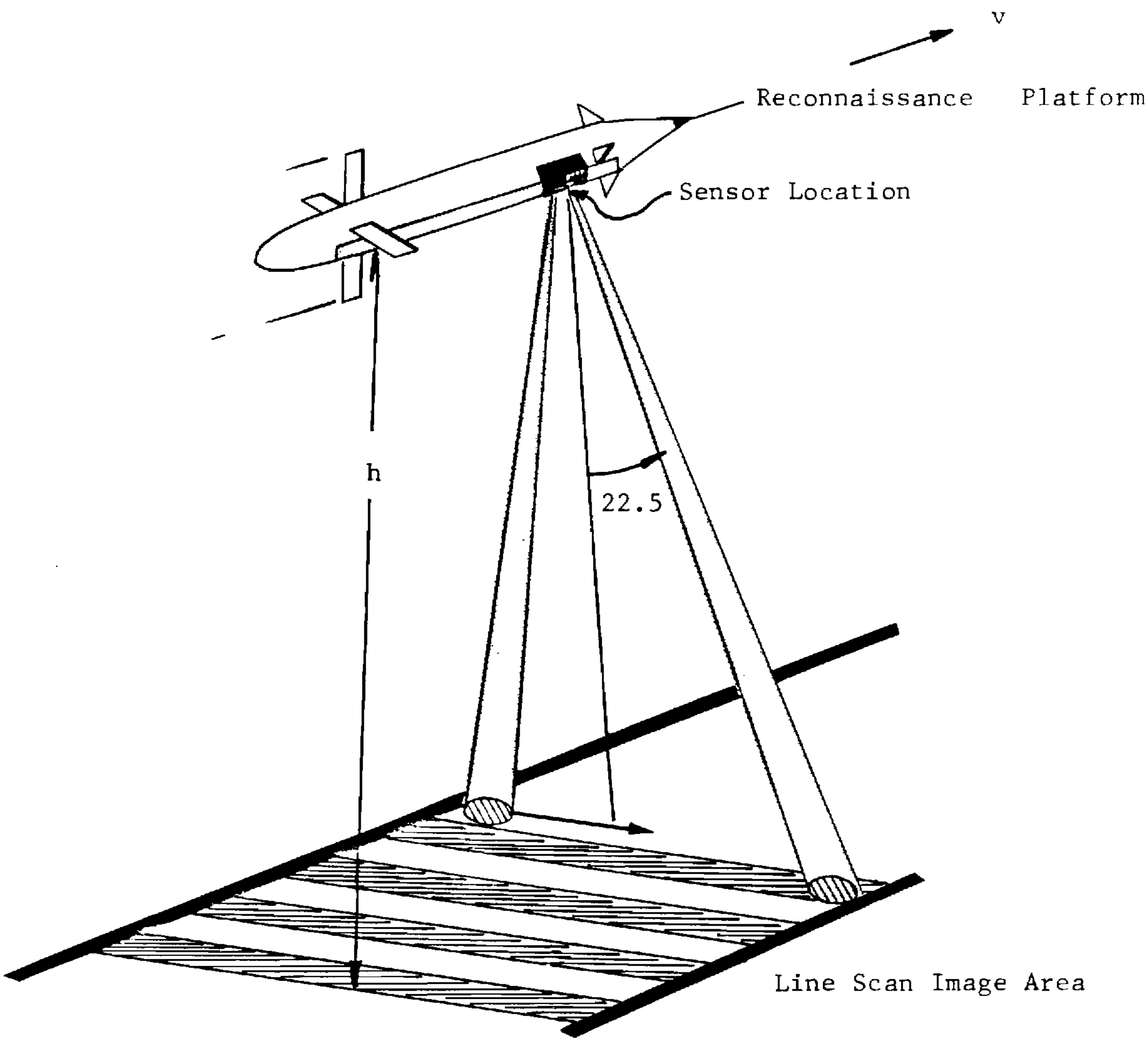
The basic concept for passive imaging is illustrated in Figure 1. The sensor package is located to view the terrain below. The sensor antenna beam is scanned. Two beam scan techniques were examined: the first (and preferred technique) uses three separate rotating antennas, the second uses a fixed antenna that views a scanning mirror. The second concept is illustrated in Figure 2.

The investigation proceeded in several phases, as outlined below:

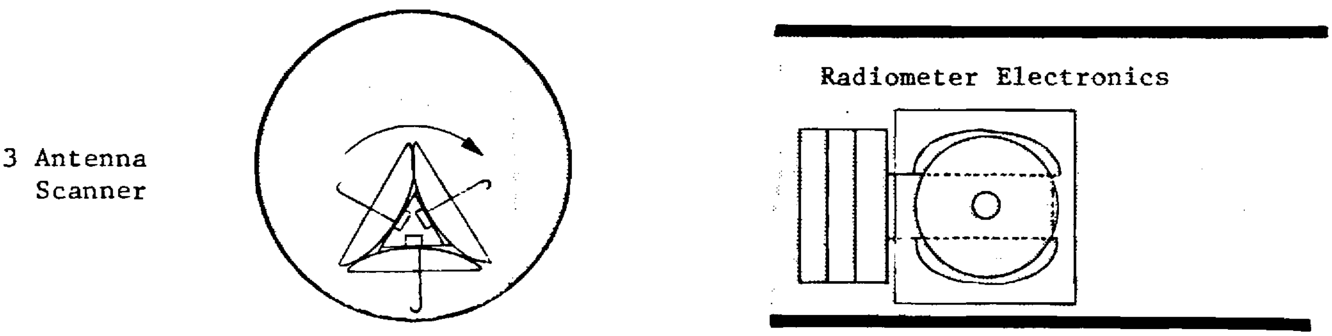
1. Examined the available mechanical outline to determine antenna size.
2. Calculated scan rates for the various antenna sizes necessary to achieve contiguous line imaging.
3. Calculated scene contrast for the sensor antenna diameters, and the various altitudes vs frequency for: a) a metal target against a grass/soil background, and b) a land/water interface.
4. Calculated the minimum sensor detectable temperature for a state-of-the-art sensor configured for this tactical application.
5. Determined the ratio of scene contrast to available sensitivity to assess parameter optimization.

TABLE 1
CALCULATION BASIS

VEHICLE	
	GROUND SPEED = 800KM/HR ALTITUDE = 600 OR 1200M
PATH WIDTH	
	500M AT 600M ALTITUDE 1000M AT 1200M ALTITUDE
METAL TARGET	
	-EQUIVALENT TO A RADAR CROSS SECTION OF $5M^2$ -ACTUALLY USED $40M^2$(x.7) PHYSICAL AREA
ANTENNA DIAMETER	
	-15CM NOMINAL -PACKAGE ALLOWS 30CM



a. Flight Geometry



b. Sensor Package

Figure 1. Passive Millimeter Wave Imaging Sensor

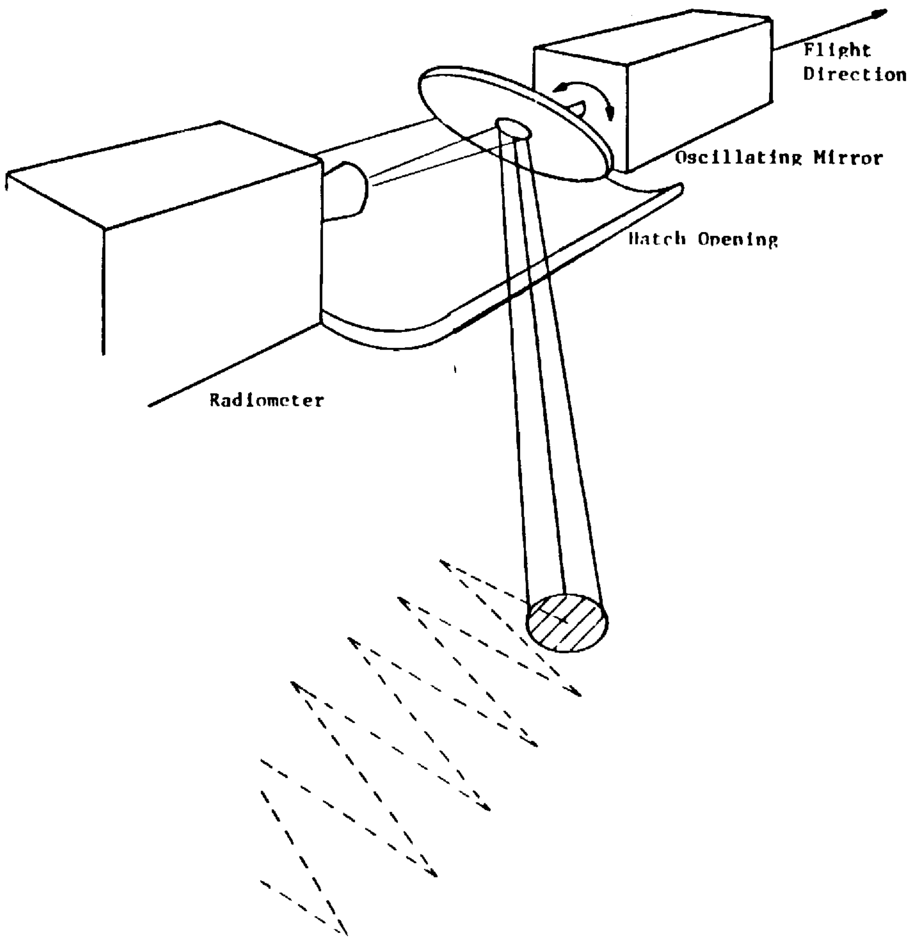


Figure 2. Single Beam Scanning Radiometer Concept.

2.0 TECHNICAL DISCUSSION

2.1 Mechanical Outline

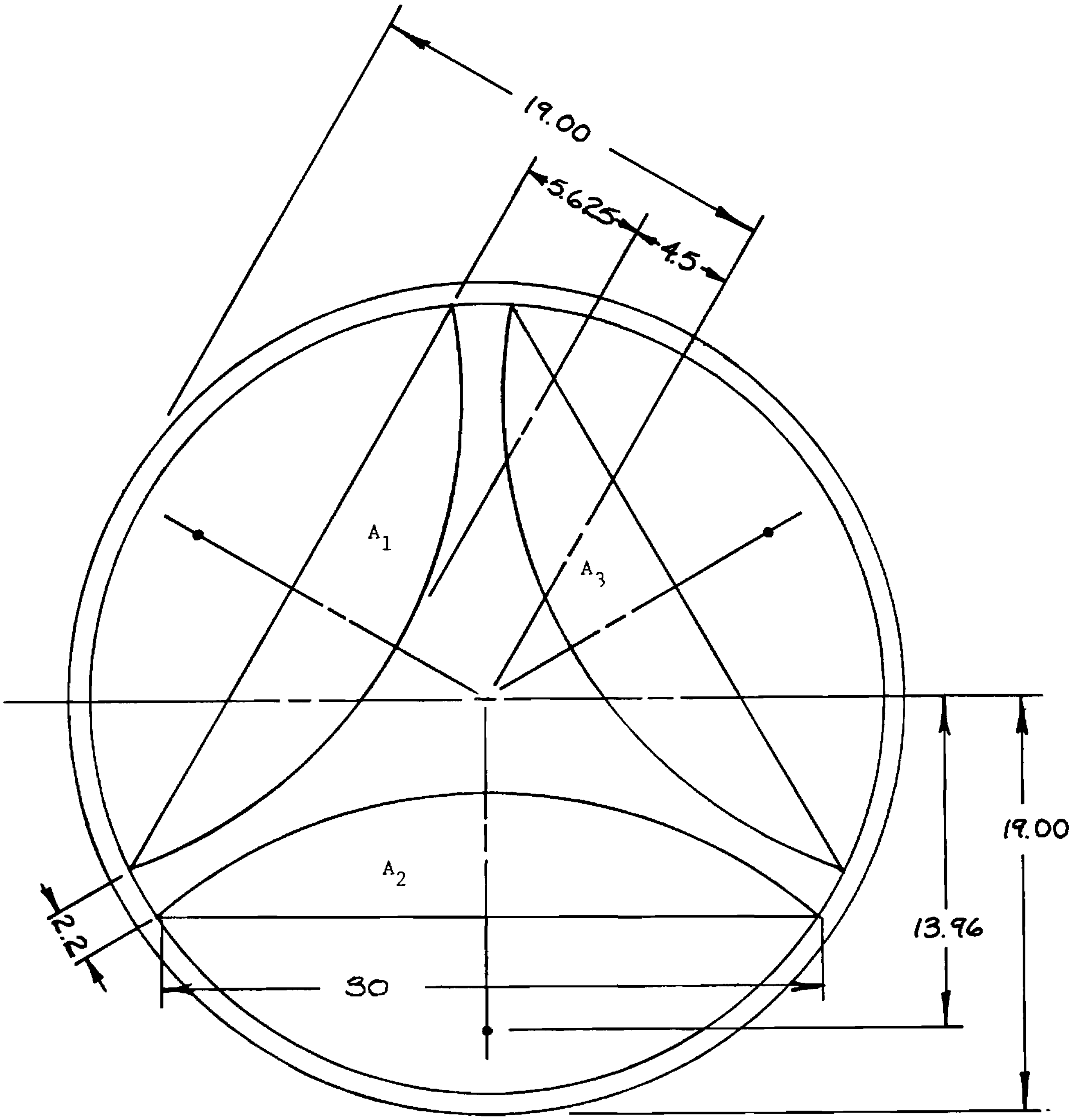
Figures 3 and 4 present two concepts for getting 3 antennas into the available volume. Figure 4 illustrates the preferred approach with a 23 cm diameter antenna that can be fitted into the smaller available space when provisions for vehicle control are made. Hence, the remainder of the investigation used a 23 cm antenna as a basis for calculations. Some data are presented for a mirror-scanned 15 cm antenna. Even though a smaller antenna can be scanned more slowly because of its broader beam, resulting in a longer integration period, the calculations indicate that one should use the largest antenna possible when trying to detect an unresolved metal target.

2.2 Scan Rates

Using an antenna diameter of 23 cm, calculations of half power beam width (HPBW) were made. This was also done for 30 cm and 15 cm diameter antennas as well. The -3 dB beam spot that forms the resolution cell at altitudes of 600 m and 1200 m was also calculated. These data are shown in Table 2. The antenna illumination used was a parabolic taper raised to the 1.5 power with a -14 dB edge taper. This aperture achieved a 98% beam efficiency at the beam null.

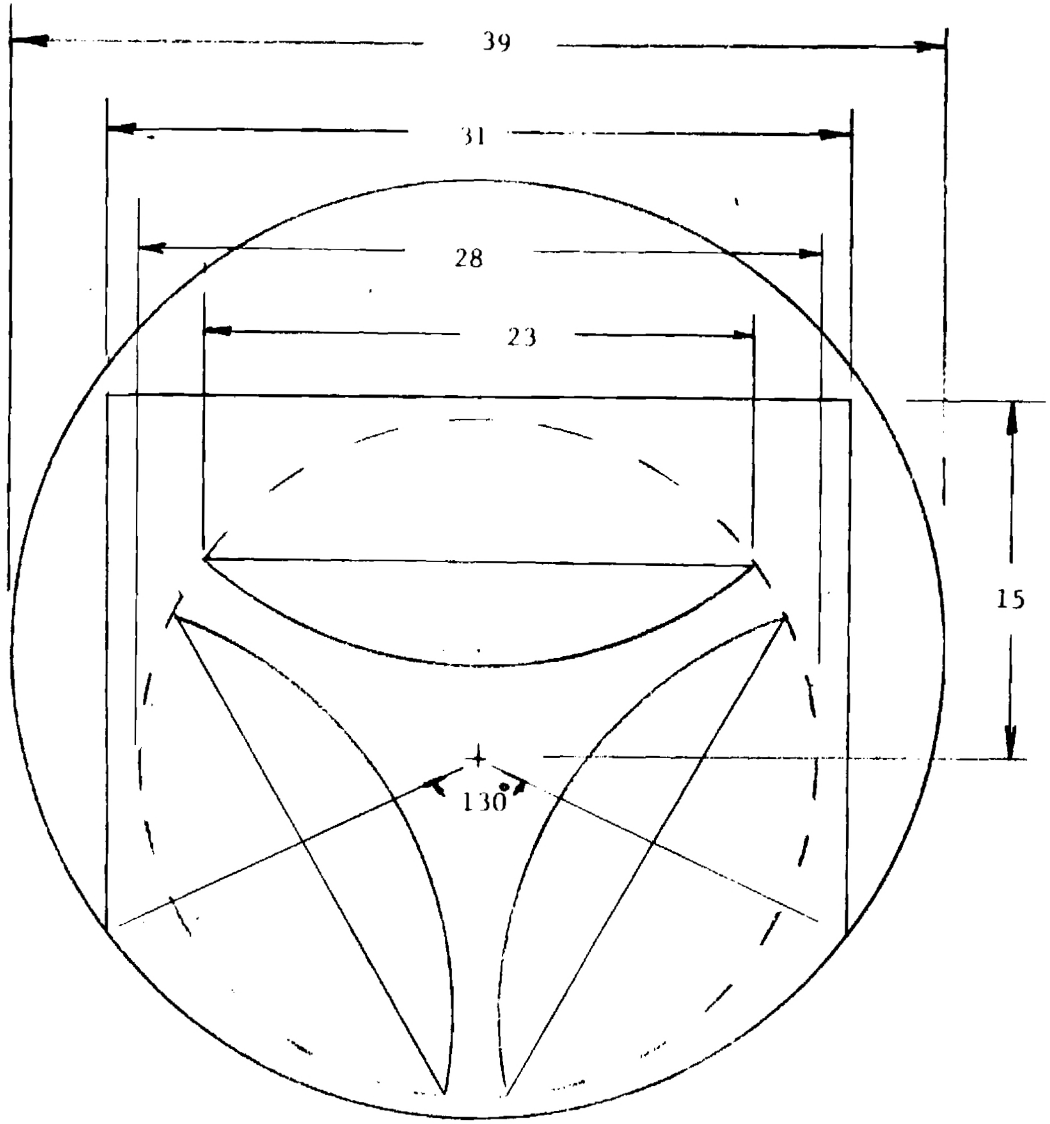
When operating at a 600 or 1200 m altitude, a scan of + 25^{o} achieves the desired swath width of 500 m or 1000 m depending on the altitude. The above parameters determine the beam scan rate, and, hence, the maximum available sensor integration time, τ_{max}, to be used in subsequent calculations.

Values of τ_{max} are shown in Tables 3 and 4. The value of integration time equals the beam dwell time. In some high signal conditions an integration time of $\tau_{max}/2$ is desirable for image sharpening. However, in this application the longer value is used to enhance detectability. Scan rates for the various 3 beam sensor situations are given in Table 5.



Dimensions in cm:

Figure 3. Cross-Section View of Drone with a Candidate 3 Antenna Scanner.



Dimensions in cm

Figure 4. Cross Section View of Drone with Preferred Candidate 23 cm Diameter Antenna Scanner.

TABLE 2

ANTENNA BEAMWIDTH AND RESOLUTION

D (CM)	F (GHZ)	HPBW (DEGREES)	NADIR RESOLUTION CELL DIAMETER * (METERS)	
			H = 600 M	H = 1200 M
15	35	3.947	41.35	82.70
	95	1.454	15.23	30.45
	140	0.987	10.34	20.67
	220	0.628	6.58	13.15
23	35	2.574	26.96	53.92
	95	0.948	9.93	19.86
	140	0.644	6.74	13.49
	220	0.410	4.29	8.59
30	35	1.973	20.66	41.33
	95	0.727	7.61	15.23
	140	0.493	5.16	10.32
	220	0.314	6.58	3.29

*BASED ON HPBW

TABLE 3

INTEGRATION TIME (D = 23 CM)

FREQUENCY (GHz)	MAXIMUM INTEGRATION TIME (SEC)* τ_{MAX}	
	H = 600 M	H = 1200 M
35	2.60×10^{-3}	5.21×10^{-3}
95	3.53×10^{-4}	7.06×10^{-4}
140	1.63×10^{-5}	3.26×10^{-4}
220	6.60×10^{-5}	1.32×10^{-4}

*3 BEAM SCANNER, CONTIGUOUS LINE SCAN, ANTENNA = 23 CM DIAMETER.

TABLE 4

INTEGRATION TIME (D = 30 CM)

FREQUENCY (GHz)	MAXIMUM INTEGRATION TIME (SEC)* τ_{MAX}	
	H = 600 M	H = 1200 M
35	1.53×10^{-3}	3.06×10^{-3}
95	2.07×10^{-4}	4.15×10^{-4}
140	9.55×10^{-5}	1.91×10^{-4}
220	3.87×10^{-5}	7.74×10^{-5}

*3 BEAM SCANNER, CONTIGUOUS LINE SCAN, ANTENNA = 30 CM DIA.

TABLE 5

SCAN RATE FOR A 3 BEAM SCANNER

FREQUENCY (GHZ)	SCAN RATE (REV/SEC) H = 600 M	SCAN RATE (REV/SEC) H = 1200 M
35	2.75	1.37
95	7.46	3.73
140	10.98	5.49
220	17.25	8.62

ANTENNA = 23 CM DIAMETER

Integration time data are plotted in Figure 5 for the 3 antenna scanners. Figures 6 and 7 show integration times for a single beam scanner. Although integration time may be increased as the retrace time is shortened, this type of sensor may not be as practical as a continuously rotating 3 antenna sensor.

2.3 Scene Contrast [2, 3, 4, 5]

Calculation of the scene contrast depended on three main factors external to the sensor: sky temperature, atmospheric loss, and target emissivity. For the incidence angles ± 22.5° off nadir, no significant polarization effects are expected to be encountered. Tables 6 presents sky temperatures and atmospheric losses used in the calculations. Two types of targets were examined: First, as indicated, in Table 7, a metallic target of a 40 m^2 area, with a shape factor such that only 0.7 of the area is oriented toward the sky (0.3 of the area is assumed to be oriented to the background). In this case, the target is generally unresolved, i.e., its area is smaller than the sensor beam area.

The background for the metallic examination was of a grass/sand/soil nature, as indicated in Table 8. This surface has a high emissivity, and, thus, does not change its radiometric temperature with frequency or sky temperature.

The second target was a land/water interface that was assumed to be large enough to fill the beam for all cases. The land was the same grass/sand/soil interface mentioned above; the water parameters are given in Table 9. The water's emissivity is taken to be lower at 35 GHz than at 95-220 GHz.

For the above scene contrast parameters, the target contrasts for the 40 m^2 metal targets were calculated first. These are shown in Figures 8 through 11. Several general trends in the plotted data should be noted. First, there is a significant improvement in contrast when moving from 35 to 95 GHz. This occurs because the nominal 3:1 improvement in resolution more than overcomes atmospheric losses. This trend continues in the less severe weather up to 220 GHz where the beam is nearly filled by the metal target. However, it is moderated by the

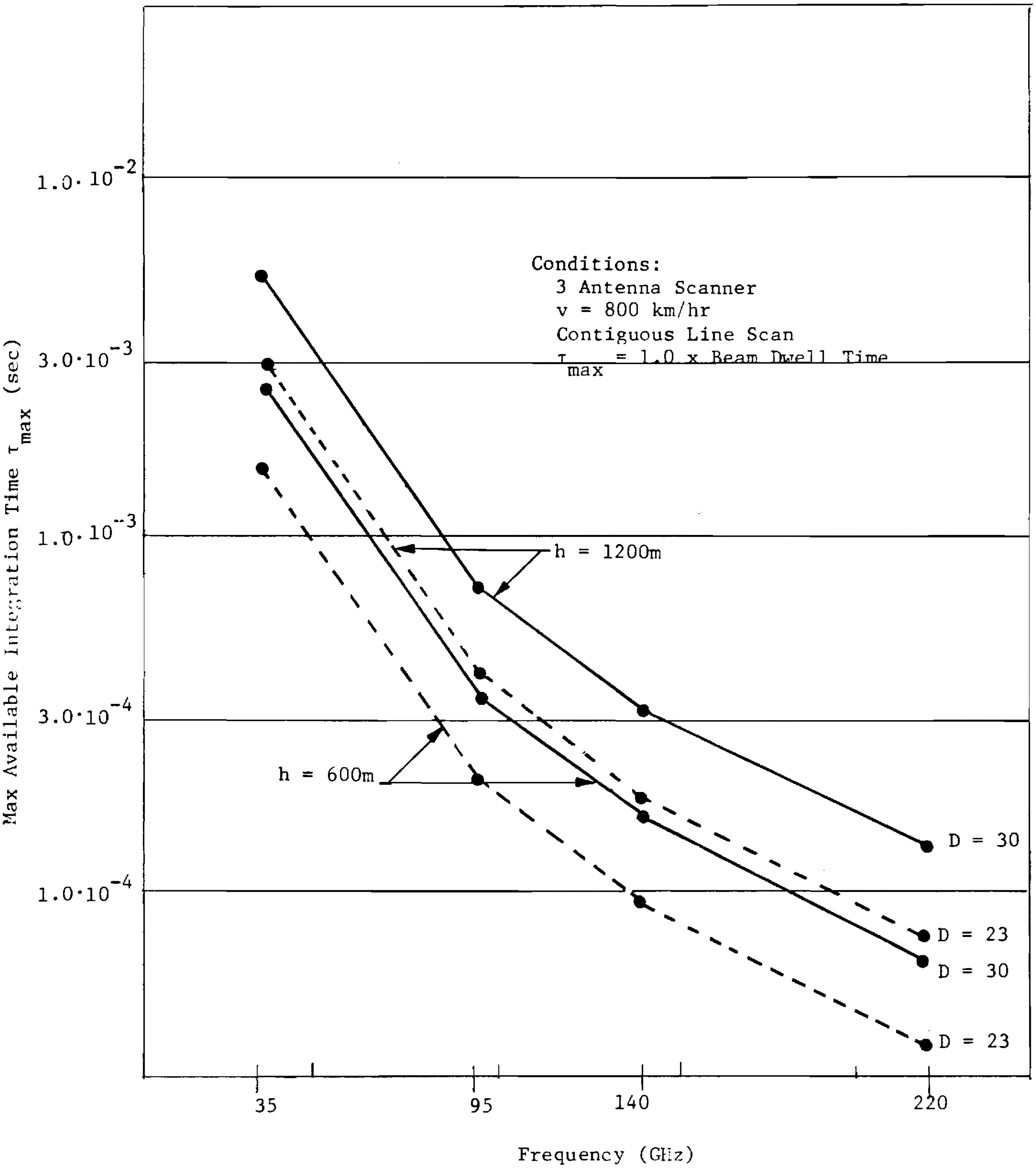


Figure 5. Maximum Available Integration Time vs. Frequency (Three Beam Scanner at h = 600 and h = 1200 m).

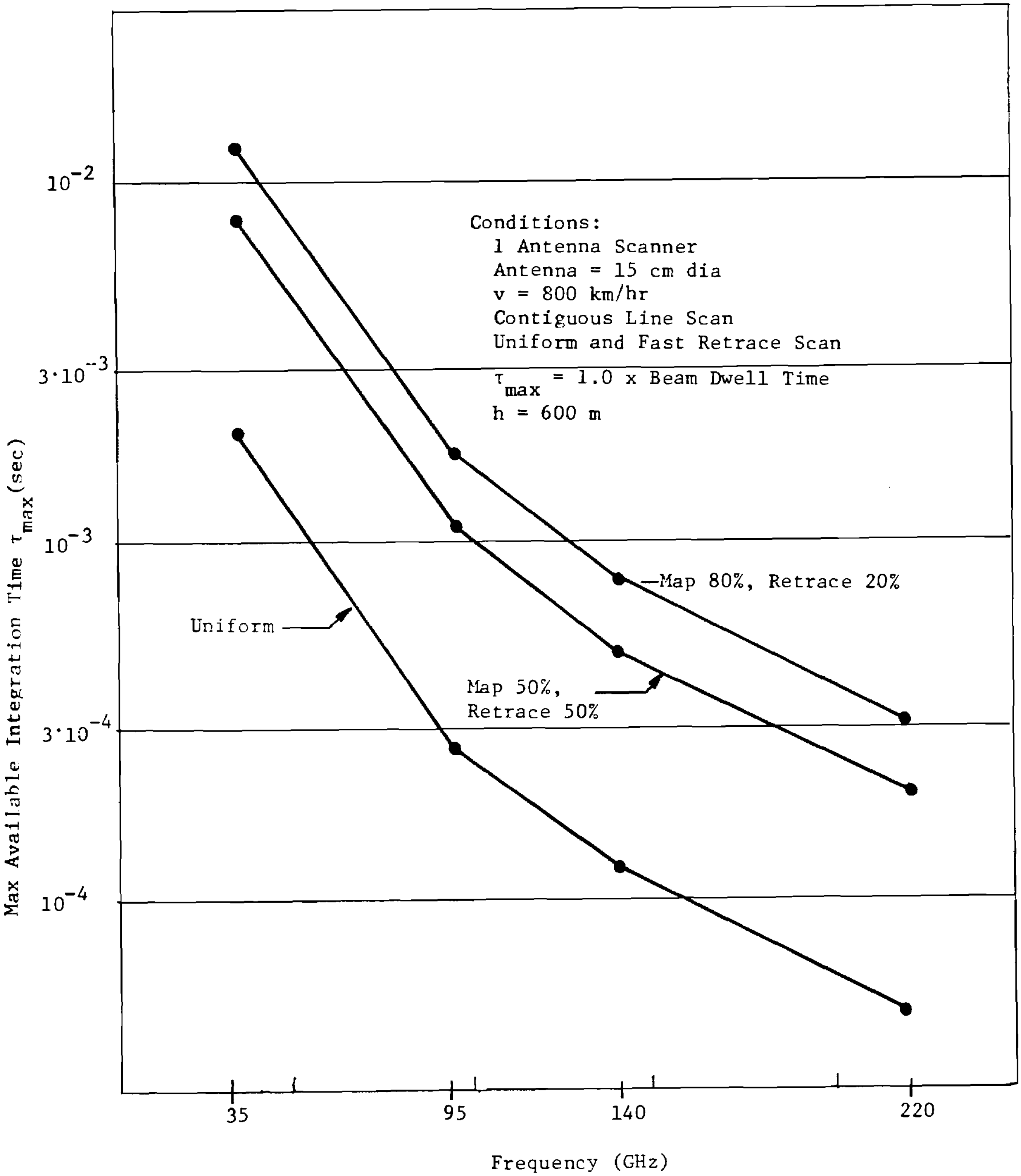


Figure 6. Maximum Integration Time vs. Frequency (Single Beam Scanner at h = 600).

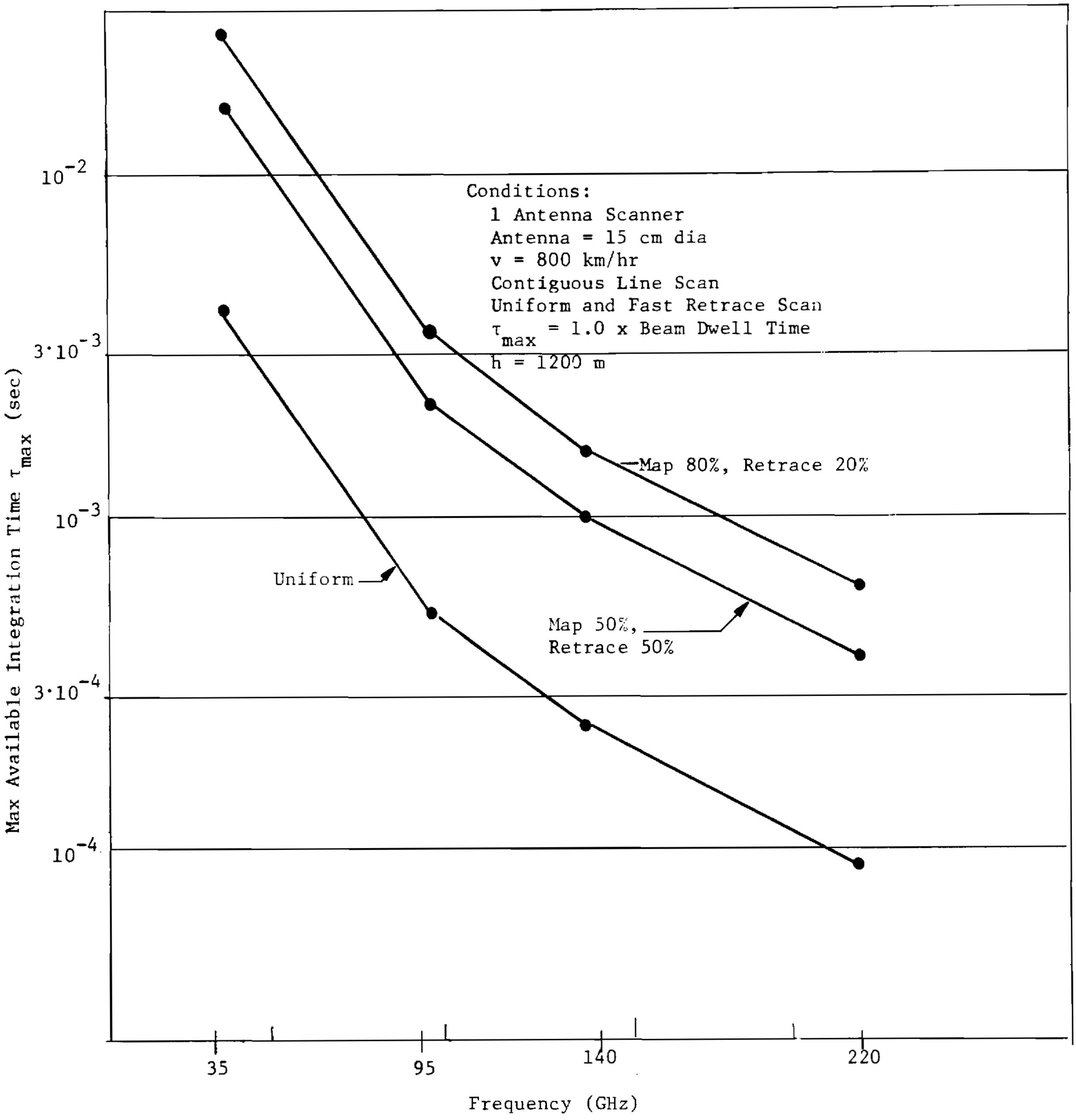


Figure 7. Maximum Integration Time vs. Frequency (Single Beam Scanner at h = 1200 m).

Table 6

NOMINAL LOSS FACTORS AND SKY TEMPERATURES FOR 35, 95, 140, 220 IN dB/km FOR VARYING ATMOSPHERIC CONDITIONS

	T_{SKY} (K°)	L (dB/km)
	35 GHz	
Clear	20	.02
Overcast	50	.05
Fog	80	.1
Light Rain	110	.25
Moderate Rain*	130	2
	95 GHz	
Clear	50	.4
Overcast	150	.45
Fog	180	.5 - .8
Light Rain	210	1
Moderate Rain	240	3
	140 GHz	
Clear	120	1.4
Overcast	150	1.45
Fog	190	1.5
Light Rain	220	1.5
Moderate Rain	260	3.5
	220 GHz	
Clear	150	4
Overcast	180	4.1
Fog	200	4.5
Light Rain	230	4.6
Moderate Rain	270 (or 260)	6

*4mm/hr

TABLE 7
METAL TARGET PARAMETERS

AREA = 40 M^2 PROJECTED AREA

SHAPE FACTOR = 0.7: MEANS ONLY 70% OF AREA REFLECTS TO THE SKY (30% REFLECTS TO THE BACKGROUND)

EMISSIVITY = 0.0

TARGET CONTRAST

BASED ON USING ANTENNA NULL BW = 2.5 X HPBW

BEAM EFFICIENCY = 0.98

TABLE 8

BACKGROUND TEMPERATURE (GRASS/SAND/SOIL)

1. BACKGROUND: GRASS/SAND/SOIL

$\epsilon = 0.94$ @ 270K

SKY TEMPERATURE (K)	BACKGROUND TEMPERATURE (K)
20	255.0
50	256.8
80	258.6
120	261.0
130	261.6
150	262.8
180	264.6
190	265.2
200	265.8
240	268.2
260	269.4
270	270.0

Table 9

BACKGROUND TEMPERATURE (WATER)

2. BACKGROUND: WATER

(A) E = 0.42 @ 270K (35 GHz)

(B) E = 0.62 @ 270K (95, 140, 220 GHz)

SKY TEMPERATURE (K)	BACKGROUND TEMPERATURE (K)
20 (A)	125
50 (B)	186.4
80 (A)	159.8
120 (B)	213.0
130 (A)	188.8
150 (B)	224.4
180 (B)	235.8
190 (B)	239.6
200 (B)	243.4
240 (B)	258.6
260 (B)	266.6
270 (B)	270.0

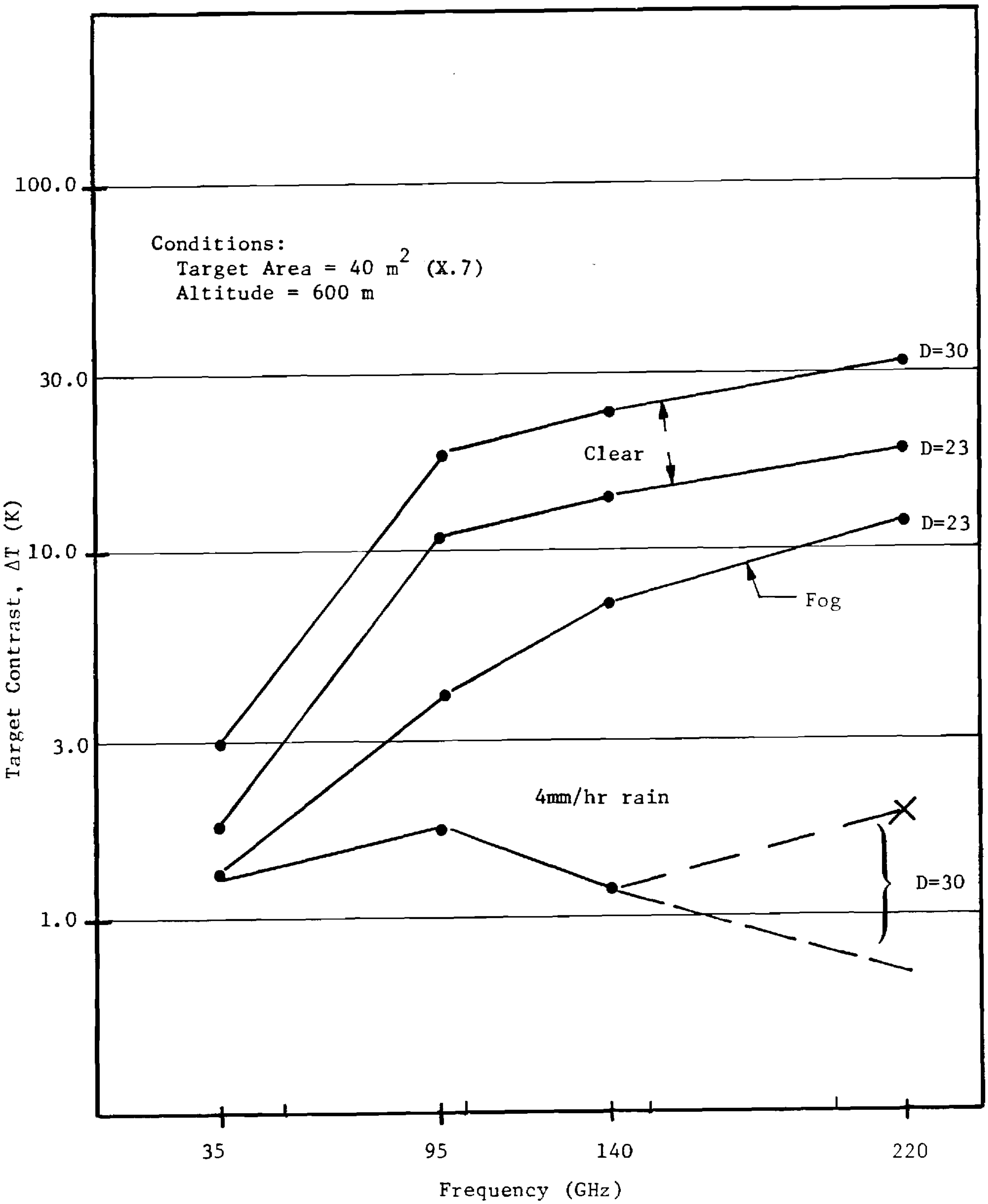


Figure 8. Target Contrast vs Frequency (Three Beam Scanner at h = 600m).

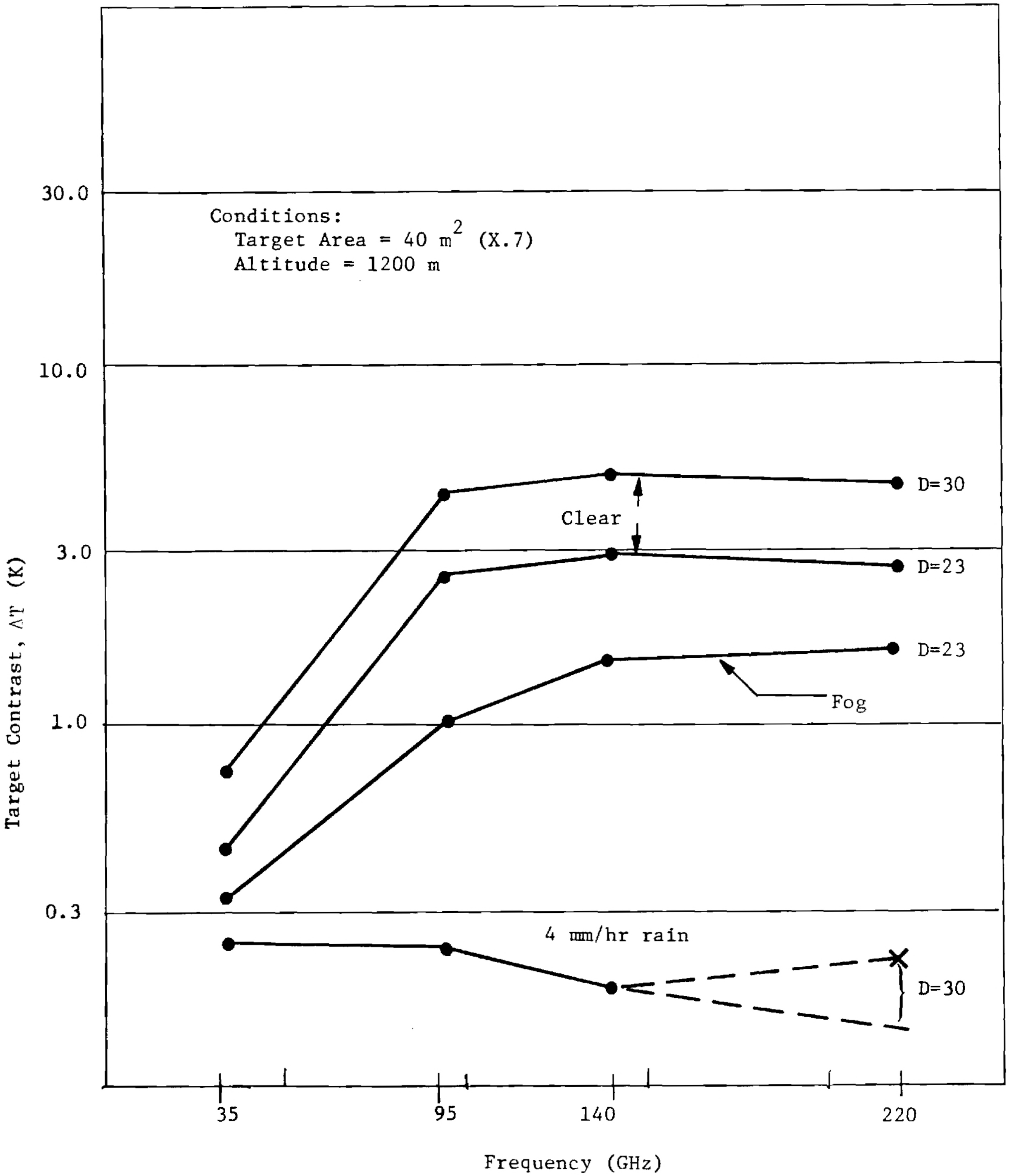


Figure 9. Target Contrast vs Frequency (Three Beam Scanner at h = 1200 m).

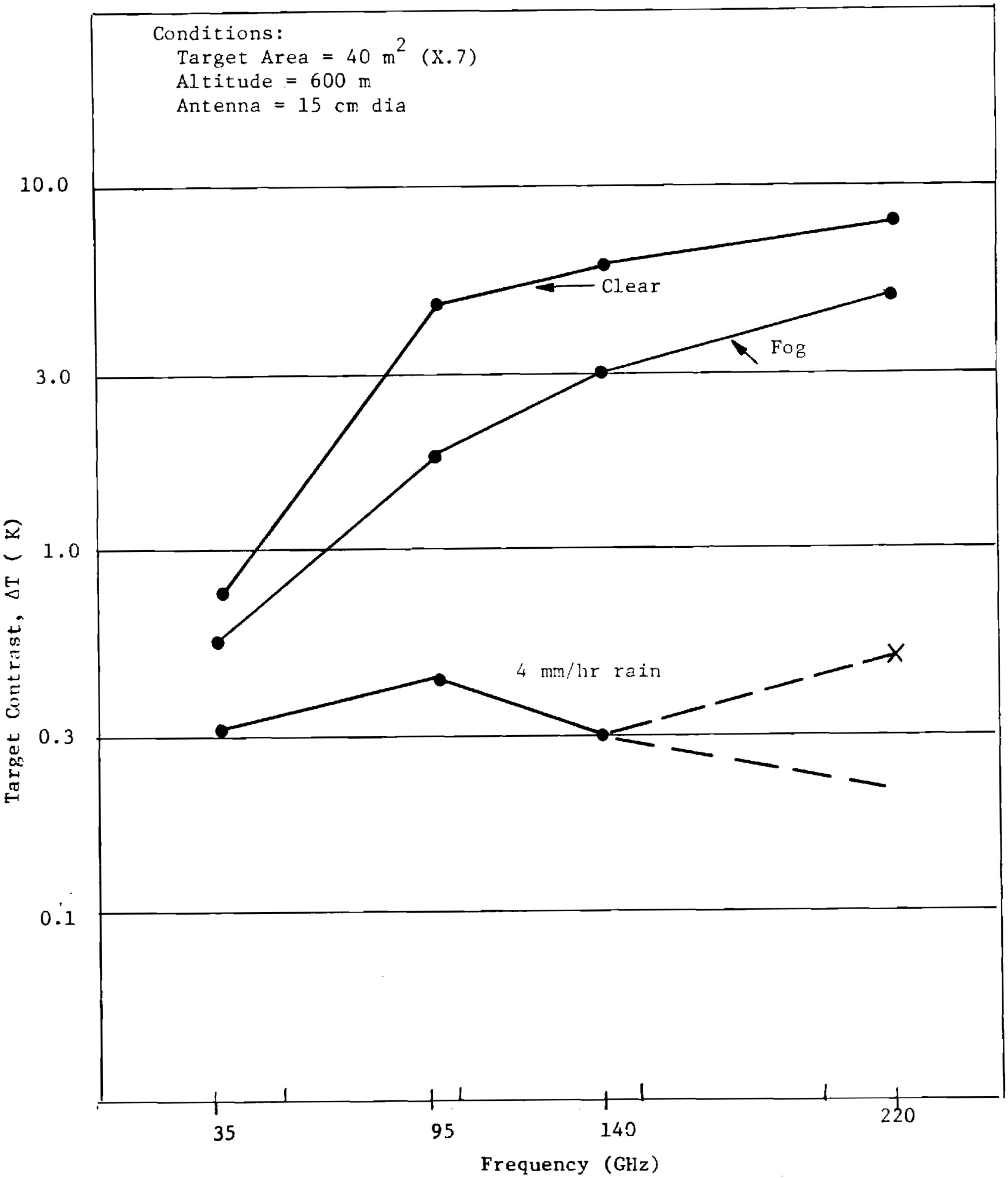


Figure 10. Target Contrast vs. Frequency (Single Beam Scanner at h = 600 m).

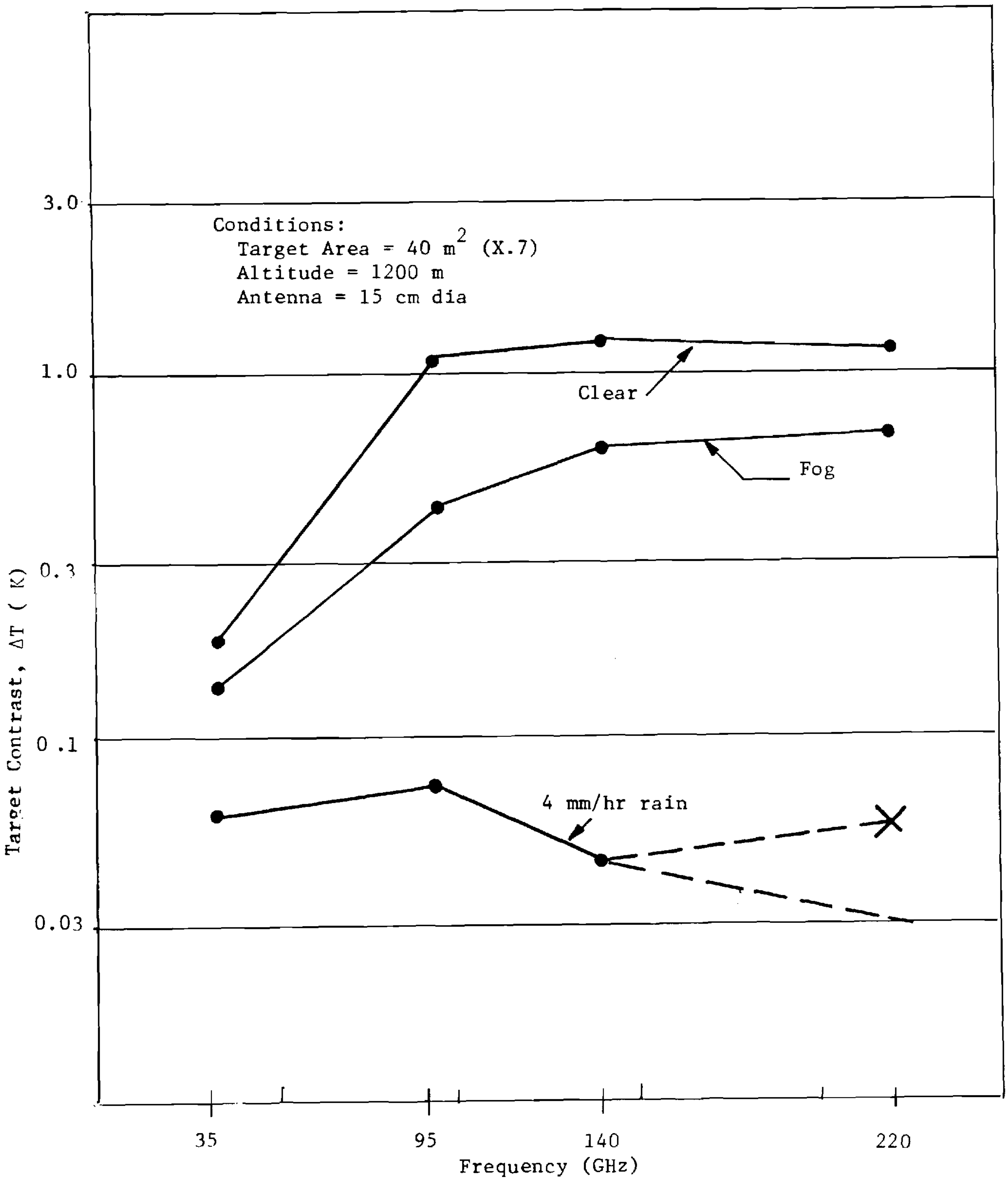


Figure 11. Target Contrast vs. Frequency (Single Beam Scanner at h = 1200 m).

degrading sky temperature and loss. In moderate rain (4 mm/hr), the atmospheric parameters modify the available contrast such that it remains low at all frequencies. In general, when using the 23 cm diameter antenna, the available contrast is in the 3 to 10 K range at 600 m altitude and is in the 1 to 3 K range at 1200 m altitude, for both the clear and fog conditions.

Results of the calculations for the water/land interface are given in Table 10 and Figure 12. Trends in these data are somewhat different because of the assumed constant beam fill. Here, because the beam is filled, the increasing atmospheric losses as frequency increases are not moderated, and contrast thus decreases with frequency. Note, however, that the available contrast starts much higher, and even with the atmospheric losses factored in, the available contrast remains significantly higher than for the 40 m^2 metal target situation.

2.4 Sensor Minimum Detectable Temperature (ΔT_{min})

To ascertain how well the available contrast will permit detection, calculations for a candidate sensor were performed. The sensor parameters are given in Table 11 which also gives the achievable values of ΔT_{min} using the values of τ_{max} given earlier. The sensor candidate is a higher performance total power unit that would use state-of-the-art techniques in many instances. The keys to achieving the low value of $\frac{\Delta G}{G}$ required to obtain the full benefit of the total power radiometer are:

1. low RFI packaging
2. stable power supplies
3. good package temperature stabilization.

This has been demonstrated at Georgia Tech in an airborne 140 GHz total power radiometer. Other design aspects are described in Reference 6.

The parameters used are realistic for operation at 35 and 95 GHz but are optimistic for operation at 140 and 220 GHz. The total power configuration is now achievable using a periodic calibration that could be done at the end of each scan line. For the 23 cm diameter antenna sensor, operating at an altitude of 1200 m, the calculated ΔT_{min} varies between 0.2 and 1.25 K.

Table 10

TARGET CONTRAST[*] - ΔT

FOR A WATER - GRASS/SAND/SOIL INTERFACE

FREQUENCY (GHz)	ΔT (K)		
	CLEAR	FOG	4 MM/HR RAIN
35	130.0	98.8	72.3
95	70.4	28.8	9.6
140	48.0	25.8	2.8
220	38.4	22.4	2.8 (MAX)

[*] BEAMFILL = 1 ASSUMED.

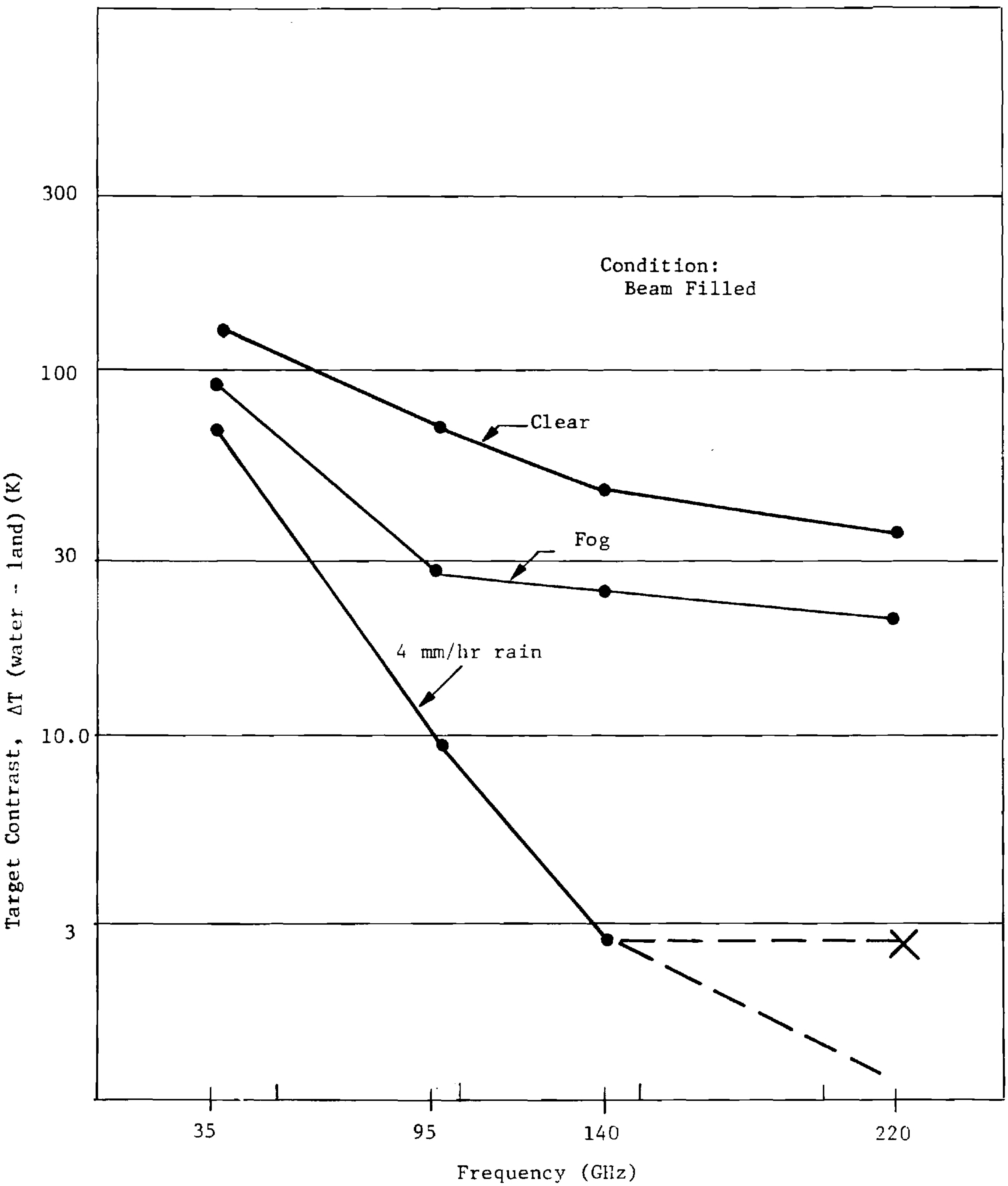
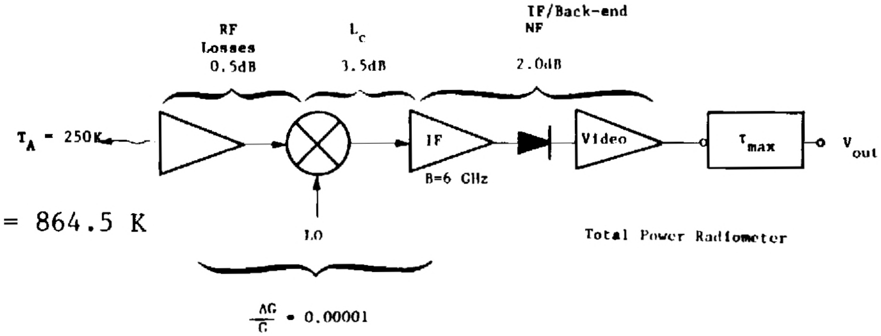


Figure 12. Target Contrast - Water/Land Interface.

Table 11

SENSOR SENSITIVITY (ΔT_{MIN})



T_{sys} = 864.5 K

Frequency (GHz)	ΔT_{min}* (K)			
	D = 30 cm		D = 23 cm	
	h = 600 m	h = 1200 m	h = 600 m	h = 1200 m
35	0.37	0.26	0.28	0.20
95	1.00	0.71	0.77	0.54
140	1.47	1.04	1.13	0.80
220	2.31	1.64	1.77	1.25

*Above current parameters, 3 beam scanner τ_{max} using

$$\Delta T_{min} = \sqrt{\left[\frac{1.0(T_A + T_{sys})}{\sqrt{B\tau_{max}}}\right]^2 + \left[(T_A + T_{sys})\left(\frac{\Delta G}{G}\right)\right]^2}$$

TABLE 12

$\Delta T/\Delta T_{MIN}$ (METAL TARGET)

FREQUENCY (GHz)	$\Delta T/\Delta T_{MIN}$ (K) CLEAR		FOG	
	H= 600	H= 1200	H= 600	H= 1200
35	6.31	2.25	4.79	1.67
95	14.49	4.85	5.76	1.88
140	12.67	3.69	6.67	1.91
220	11.11	2.26	6.96	1.32

3 BEAM SCANNER, DIA= 23CM

Table 13
$\Delta T/\Delta T_{MIN}$ (Water/Land)

Frequency (GHz)	$\Delta T/\Delta T_{MIN}$ (K) Clear		Fog	
	H = 600	H = 1200	H = 600	H = 1200
35	461.0	651.3	350.3	494.9
95	91.9	129.9	37.6	53.2
140	42.6	60.2	22.9	32.4
220	21.7	30.7	12.6	17.9

3 Beam Scanner, D = 23 cm

Note: It is assumed that the integration time is set at a given altitude to τ_{MAX} to enhance metal target detection. Hence, τ_{MAX} is longer at H = 1200 m than at H = 600 m. The resultant ΔT_{MIN} is better and hence the ratio $\Delta T/\Delta T_{MIN}$ is better. The value of ΔT is the same for both altitudes since the beam is filled.

2.5 Effective Signal-to-Noise Ratio or $\Delta T/\Delta T_{min}$

Target detectivity is determined by both the available contrast, ΔT, and the receiver sensitivity, ΔT_{min}. The ratio can be taken as a form of the signal-to-noise ratio. Values of $\Delta T/\Delta T_{min}$ for the metal target and the water/land interface are given in Tables 12 and 13 for the 23 cm diameter antenna sensor.

These values are plotted versus frequency in Figure 13. The water/land interface possesses a very high value of $\Delta T/\Delta T_{min}$ that falls off with frequency. For the 40 m^2 (x 0.7) metal target case, the ratio, $\Delta T/\Delta T_{min}$, shows a slight peak at 95 GHz (in clear weather).

If one takes a minimum $\Delta T/\Delta T_{min}$ value of 3:1, then, for the above parameters, operation at 95 or 140 GHz is possible at altitudes of 600 m (clear and fog) and at 1200 m (clear). Based on the somewhat optimistic assumed receiver sensitivity at 140 GHz, the better frequency choice would be 95 GHz. Operation at 1200 m in fog would require larger targets. Table 14 indicates that $\Delta T/\Delta T_{min} > 3$ at 1200 m altitude for an 80 m^2 (x 0.7) target. Note that the water/land interface could be detected at both altitudes in the clear and fog conditions.

The effect of changing antenna size is examined in Figure 14. Here, the value of $\Delta T/\Delta T_{min}$ in both clear and fog conditions, at a 1200 m altitude, is examined for antennas in the 15 to 30 cm diameter range. These data indicate that an antenna slightly larger than 30 cm diameter is needed (for the assumed condition) to detect the 40 m^2 target in fog.

2.6 Mechanical Configuration

The sensor examined above used 3 antennas to permit contiguous line scan imaging at a moderate scan rate to ease mechanical performance and to allow an adequate integration time that enhanced detectability. The sensor block diagram is shown in Figure 15. On the left are the rotating components; their outputs are switched in snychronism with the rotation rate and are fed to a rotary joint to the fixed mounted portions of the receiver.

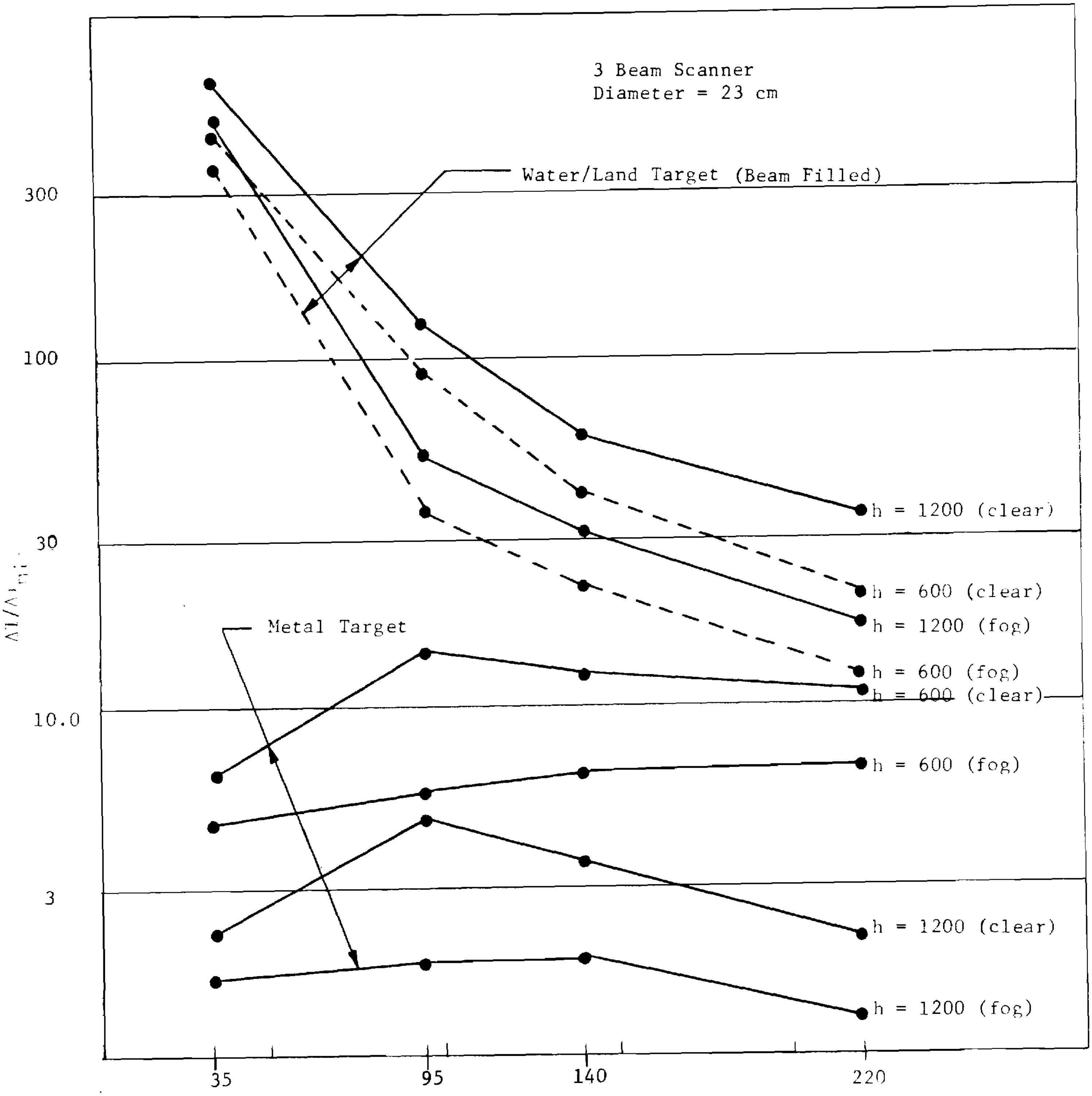


Figure 13. $\Delta T/\Delta T_{min}$ vs Frequency (D = 23 cm, Water/Land and Metal Target).

TABLE 14

ΔT AND $\Delta T/\Delta T_{MIN}$ FOR VARIOUS TARGET SIZES

(H = 1200 M)

A_T (x 0.7) (M^2)	CLEAR		FOG	
	ΔT (K)	$\Delta T/\Delta T_{MIN}$	ΔT (K)	$\Delta T/\Delta T_{MIN}$
10	0.66	1.22	0.25	0.46
20	1.31	2.42	0.51	0.94
40	2.62	4.82	1.02	1.89
80	5.25	9.72	2.03	3.76
160	10.50	19.44	4.06	7.52

CONDITIONS:

F = 95 GHz

3 BEAM SCANNER

D = 23 CM

$\tau = \tau_{MAX}$

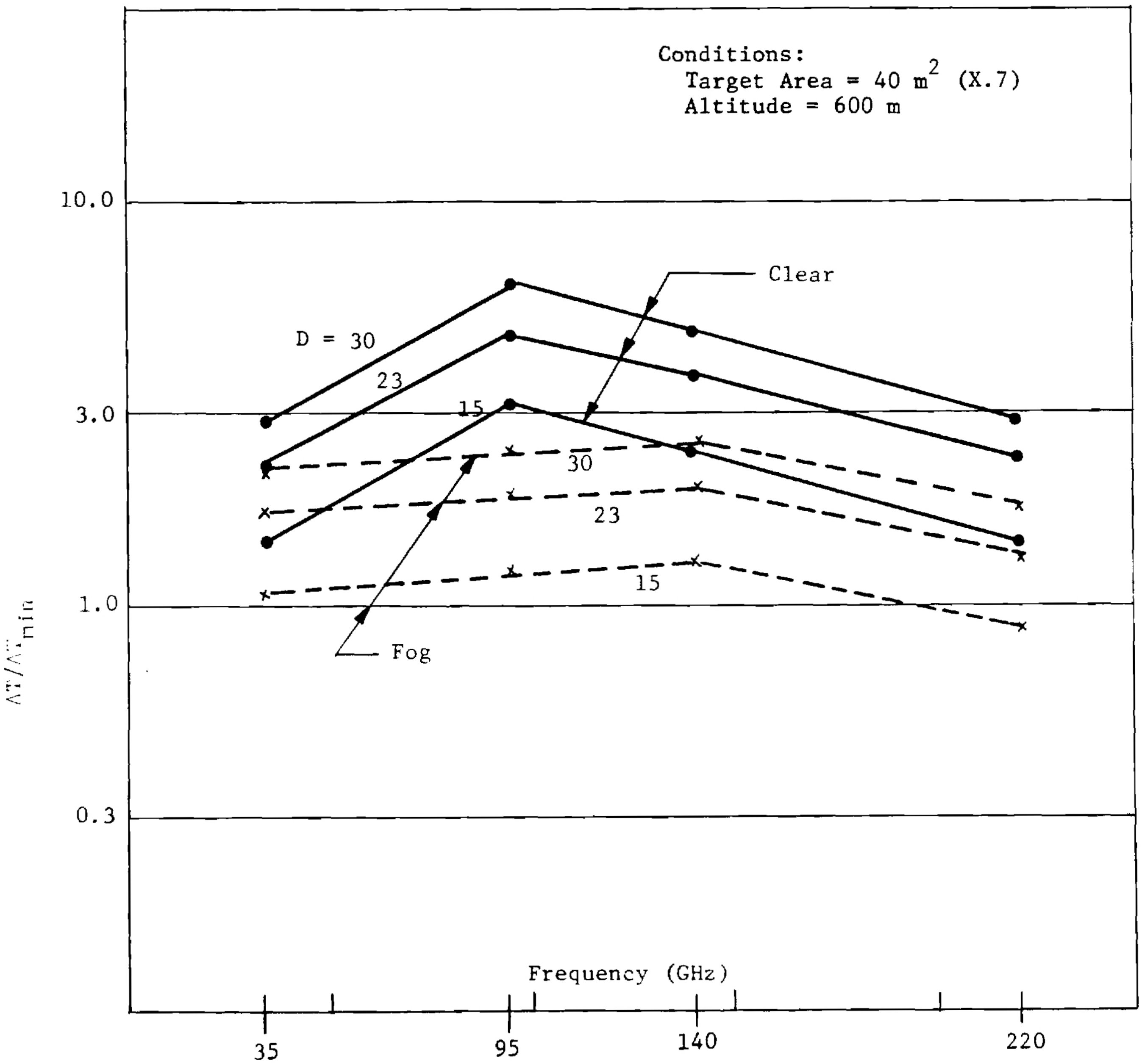


Figure 14. $\Delta T/\Delta T_{min}$ vs Frequency (Three Beam Scanner at h = 1200m)

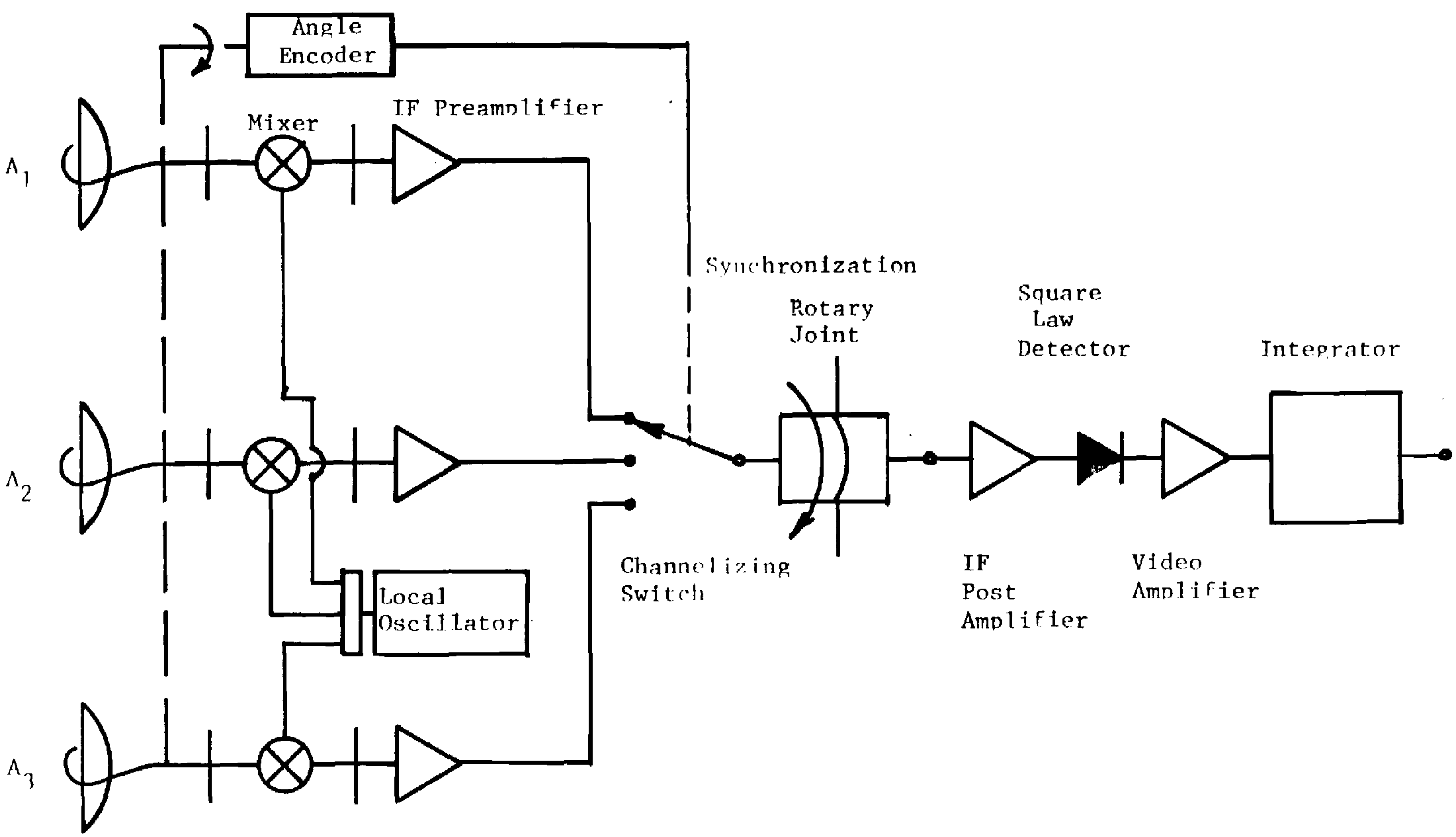


Figure 15. 3 Antenna Beam Scanner Radiometer Block Diagram.

A mechanical configuration drawing is shown in Figure 16. This layout suggest that, with modest difficulty, all components may be contained with the available volume. Table 15 presents a weight breakdown estimate.

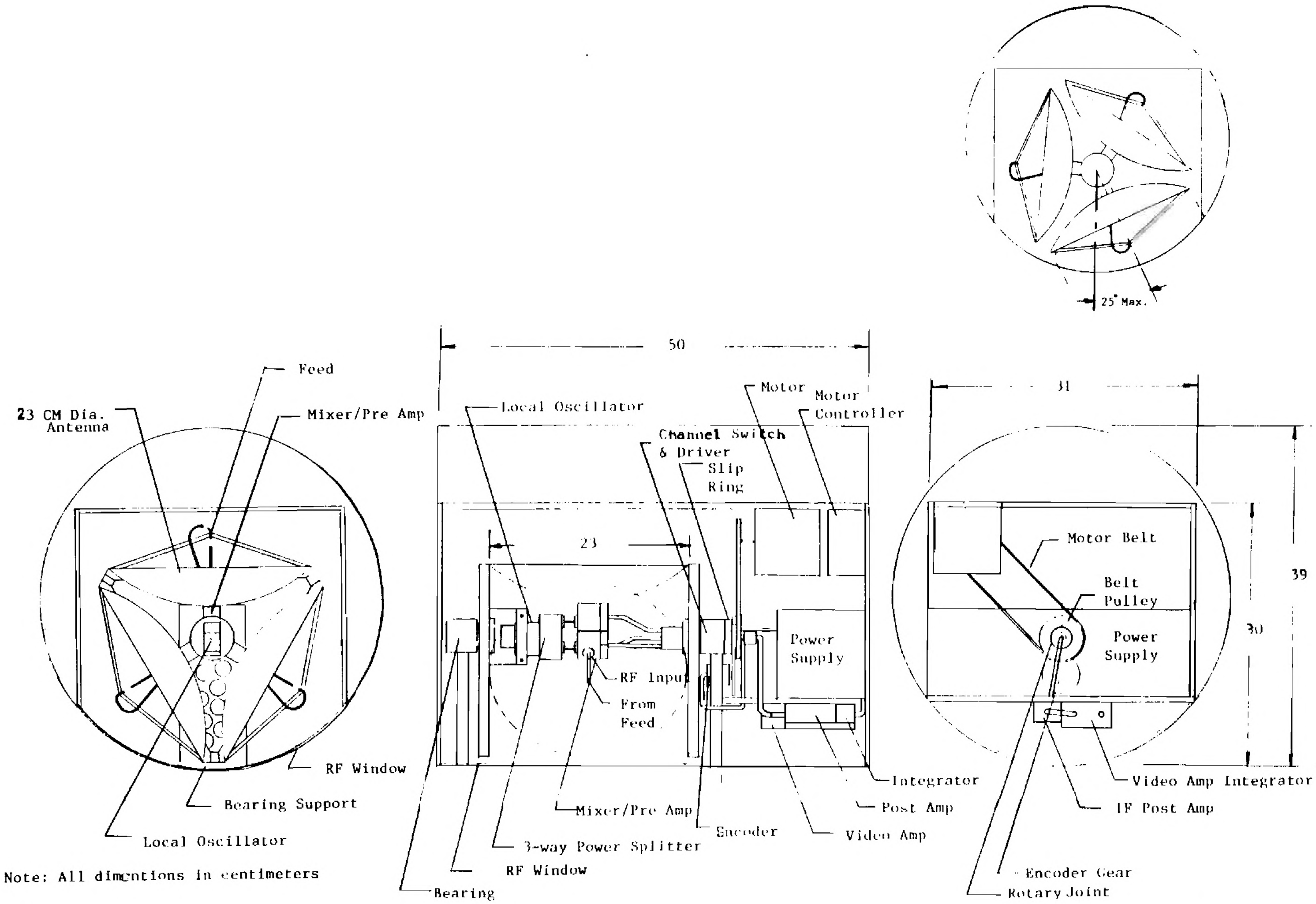


Figure 16. Millimeter Wave Sensor Mechanical Configuration Drawing.

Table 15
MILLIMETER WAVE SENSOR WEIGHT ESTIMATE

ITEM	WEIGHT (KG)
ENCLOSURE	8.3
BEARING RINGS	1.5
ANTENNA SUPPORT	2.9
LOCAL OSCILLATOR BRACKET	0.1
MISCELLANEOUS FASTENERS	0.5
AXEL	0.1
PULLEY, BELTS AND GEARS	1.7
ENCODER	0.2
SLIP KING	0.4
BEARINGS	0.6
RF MIXERS	0.2
RF POWER SPLITTER	0.2
ANTENNAS	2.5
RF WINDOW	0.5
THREE POLE RF SWITCH	0.2
CO-AX ROTARY JOINT	0.2
VIDEO AMPLIFIER	0.2
INTEGRATOR	0.2
CO-AX CABLE	0.2
POWER SUPPLY	3.6
MOTOR	1.9
MOTOR CONTROLLER	0.6
TOTAL	26.8 KG

3.0 REFERENCES

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[5] E. Schanda and R. Hofer, "Emissivities and Forward Scattering of Natural and Man-Made Material at Three Millimeter Wavelength," Proc. 9th Int. Symp. Remote Sensing of the Environment, 15-19 April 1974, University of Michigan, Ann Arborn, 1585-1592.

[6] M. S. Hersman and G. A. Poe, "Sensitivity of the Total Power Radiometer with Periodic Absolute Calibration," IEEE Trans. on MTT, Vol. MTT-29, January 1981.

Appendix

Target Contrast Equations

Appendix 1

TARGET CONTRAST EQUATIONS

1) Background

$$T_{BACK} = e\ T_{mat'l} + (1 - e)\ T_{sky}$$

where

T_{BACK} = Radiometric temperature of the background (i.e., earth's surface) (K)

e = Background emissivity ($e < 1$)

T_{sky} = Sky temperature over the background (K). Angle of incidence must be taken into account.

$T_{mat'l}$ = Background material physical temperature (K).

2) Target Alone (at Range = 0)

$$T_{tgt} = A\ T_{sky} + (1 - A)\ T_{BACK}$$

where

T_{tgt} = Target temperature at the target (i.e., Range = 0) (K)

A = A shape factor. $A < 1$. $A = 0.7$ in this investigation.

T_{BACK} = Background temperature (K).

3) Target in the Beam (at Range = 0)

$$T_{BEAM} = \eta[T_{tgt}(\frac{A_T}{A_B}) + [1 - (\frac{A_T}{A_B})]T_{BACK}] + (1 - \eta)T_{BACK}$$

where

T_{BEAM} = Radiometric temperature of the target in the beam at the target (i.e., Range = 0)

η = Beam efficiency. $\eta < 1$. $\eta = 0.98$ in this investigation.

A_T = Target area (m^2). $A_T = 40\ m^2$ in this study.

A_B = $\pi R^2 \tan^2(HPBW/2)$

R = Range

HPBW = Sensor antenna half-power beamwidth (degrees).

4) Atmospheric Loss

$$L = 10^{(R/1000)(\ell)\frac{1}{10}}$$

where

L = Atmospheric loss ($L > 1$)

R = Range (radiometer to target) m

ℓ = Atmospheric loss (dB/km)

5) Temperature at Radiometer (at Range = R)

$$T'_{BACK} = \frac{T_{BACK}}{L} + T_{ATMOS}(1 - \frac{1}{L})$$

$$T'_{BEAM} = \frac{T_{BEAM}}{L} + T_{ATMOS}(1 - \frac{1}{L})$$

$$\Delta T = T'_{BEAM} - T'_{BACK}$$

where

ΔT = Target contrast at Range = R (K)

T'_{BACK} = Background temperature at Range = R (K)

T'_{BEAM} = Radiometric temperature in the beam at Range = R (K)